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METHOD AND APPARATUS FOR
INCREASING FAULT TOLERANCE
FOR CROSS-LAYER
COMMUNICATION IN NETWORKS

[01]   METHOD AND APPARATUS FOR INCREASING FAULT TOLERANCE
FOR CROSS-LAYER COMMUNICATION IN NETWORKS

[02]   STATEMENT OF GOVERNMENTAL INTEREST

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[03]   This invention is related to work preformed in contract with the U.S. Government
under the Office of Navel Research Contract #N00014-99-C-0322, and the U.S.
Government may have certain rights in this invention.

10   [04]   PRIORITY CLAIM

[05]   This application claims the benefit of priority to provisional patent applications
60/444,746, filed February 3, 2003, with the U.S. Patent and Trademark Office,
and titled "Distributed Fault Tolerance Techniques for Cross Layer
Communication Agents in Hybrid Mobile Wireless Networks," and 60/458,248,

15   filed March 28, 2003, with the U.S. Patent and Trademark Office, and titled
"Method and Apparatus for increasing fault tolerance for Cross-layer
Communication in networks."

20   [06]   BACKGROUND OF THE INVENTION

[07]   (1) Technical Field

[08]   The present invention relates to techniques for security and fault tolerance in
hybrid networks. Specifically, the invention relates to a system and method to
allow and utilize multiple Cross Layer Communication Agents in a single sub-

25   network for increased fault tolerance.

[09]   (2) Discussion

[10]   Over the past several decades, the electronic communications field, particularly in
the area of wireless communication, has exploded. Wireless communication is no

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longer limited to terrestrial networks, such as cellular networks; instead, the field has expanded to include hybrid networks such as satellite networks combined with fixed and mobile multi-hop terrestrial networks. FIG. 1 depicts a hybrid network 100 comprising different components such as ad-hoc sub-networks 102, 104 and low earth orbiting (LEO) or geostationary earth orbiting (GEO) satellites 106.

[11]   In order to enable connectivity between the disparate components, cross layer communication agents (CCAs) 108-1, 108-2 are used. CCAs 108-1, 108-2 serve

10   as gateways capable of interfacing with the various hybrid components of the hybrid network 100. Typically hybrid networks comprise different network types such as satellite networks, fixed, and mobile networks all interconnected though a variety of CCAs. The CCAs can switch packets between different networks and thus enable communication between the different components.

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[12]   The concept of CCAs becomes even more complicated when applied to an ad-hoc network. An ad-hoc network comprises many mobile nodes that communicate using transceivers capable of transmitting or receiving short-range signals. Some of these mobile nodes function as CCAs since they are equipped with

20   communication equipment capable of transmitting to other realms, such as satellite transmitters/receivers. Therefore, all communication from the ad-hoc network to the other components within the heterogeneous network 100 has to be routed through the CCA nodes 108-1, 108-2. For example, if a node 102-1 in an ad-hoc network 102 wishes to send data to a node 104-1 in another ad-hoc

25   network 104 that is a part of the heterogeneous network 100, node 102-1 has to first route the data packets to a CCA 108-1. The CCA 108-1 will then forward the data packets to a satellite 106 which will forward the packets to a CCA 108-2 in the destination ad-hoc network 104, which forwards the packets to the destination node 104-1. However, for this chain of events to execute successfully,

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each node 102-1, 104-1 in the heterogeneous network 100 needs to be configured with the information for identifying its affiliated CCA 108. If only a single CCA 108 is present in each ad-hoc network 102, 104, then the job of configuring each node 102-1, 104-1 with CCA information is not difficult. Just as in a wired local area network (LAN), the mobile nodes can be configured either manually or during IP address assignment using dynamic host configuration protocol (DHCP).

[13]   From a fault tolerance point of view, the foregoing network architecture, where there is only one CCA, presents a problem. If the one CCA fails, then the entire ad-hoc network associated with that CCA will be disconnected from the heterogeneous network 100. To reduce the potential for complete disconnection of an ad-hoc network due to a failure of a single component, it is desirable that each ad-hoc network have multiple, redundant CCAs. Furthermore, all CCAs may not be able to communicate with LEO satellites at all times for various reasons, such as terrain blockages, buffer overflows, etc. In these cases, it is desirable to have at least one other CCA-capable node to take over the responsibility of being the gateway CCA for the group. However to facilitate CCA redundancy, a need exists to coordinate the relay of data to these multiple CCA-capable nodes within a single ad-hoc network.   First, communication is necessary to determine which CCA-capable node is going to be the gateway. Second, all other nodes in the ad-hoc network need to be informed which CCA-capable node is the current gateway CCA. So when one CCA-capable node takes over the responsibility of being the gateway CCA for the group, the mobile nodes within its purview need to be informed to route their inter-domain packets to the new gateway CCA. However, standard Internet inter-domain routing protocols, such as border gateway protocol (BGP) are not useful in these cases because of the high frequency of changes that occur in ad-hoc networks. Thus, what is needed is a system and method for configuring the mobile nodes with the gateway CCA information in the face of different types of faults that can occur within the

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ad-hoc network. Typically these faults include, (i) Fail-Stop: This happens when a gateway CCA is destroyed or otherwise incapacitated; (ii) Intermittent: This can occur when a gateway CCA is disabled temporarily because of terrain blockages, etc.; and (iii) Byzantine: This happens when a gateway CCA is confiscated and is being manipulated by an unknown entity (i.e. a hacker or some other enemy).

[14]   (3) Related Work

[15]   Several routing protocols, e.g., dynamic source routing (DSR), destination-sequenced distance vector (DSDV) and temporally ordered routing algorithm (TORA), have been proposed for ad-hoc networks. Almost all of these algorithms are for routing within the ad-hoc network only. They do not extend to heterogeneous networks containing a mix of both ad-hoc components and infrastructure-based networks. As previously discussed, the ad-hoc network preferably has multiple CCA-capable nodes present within the ad-hoc sub-network that are capable of routing packets between the ad-hoc sub-network and the other networks comprising the heterogeneous network, i.e. fixed, satellite or airborne networks. Anycasting is a possible solution, where all the CCA-capable nodes can be grouped into a single anycast address and mobile nodes can use this address as the router for communicating with hosts not in their ad-hoc sub-network. But not all routing protocols support such anycast mechanisms. In Y. Kao and N. H. Vaiday, Anycasting and Geo-casting in Mobile Ad-hoc Networks, Technical Report TR00-014, Department of Computer Sciences, Texas A&M University, 27, 2000, Vaiday et al. propose extensions to TORA to support anycasting. Further, in C. Intanagonwiwat and D. D. Lucia, The Sink-based Anycast Routing Protocol for Ad-hoc Wireless Sensor Networks, Technical Report 99-698, USC/Information Sciences Institute, 1990, a sink-based anycast routing protocol is proposed.

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[16]   There has been little research in the area of security and fault tolerance for ad-hoc
networks. In L. Zhou and Z. Hass, Securing Ad-hoc Networks, IEEE Network
Magazine, 13(6), 1999, security-related issues involving routing in ad-hoc
networks are discussed. The Hass et al. article proposes that ad-hoc networks
should have a distributed architecture with no central entities to achieve high
survivability. They propose to use (n, t+1) threshold cryptographic methods to
decentralize any cryptographic operation (e.g., signing a key), where at least t+1
nodes have to collaborate to perform the operation and no set of t nodes can
achieve the same result, even operating in collusion.

[17]   Any fault-tolerant algorithm inherently has to be distributed. The complexity of
such algorithms in ad-hoc networks is increased due to the highly dynamic nature
of such networks and the unreliability of the communication medium. In K. P.
Hatzis, G. P. Pentaris, P. G. Spirakis, V. T. Tampakas, and R. B. Tan,
Fundamental Control Algorithms in Mobile Networks, ACM Symposium on
Parallel Algorithms and Architectures, p. 251-260, 1999, the authors propose two
distributed leader election algorithms for ad-hoc networks. Their algorithms
require that all nodes know the coordinates of the space in advance. In N.
Malpani, J. L. Welch, and N. Vaida, Leader Election Algorithms for Mobile Ad-
hoc Networks, Proceedings of the 4th International Workshop on Discrete
Algorithms and Methods for Mobile Computing and Communications, p. 96-103,
Boston, MA, August 2000, the authors propose distributed leader election
algorithms that are based on TORA. However, both of these works consider only
the dynamic and multi-hop nature of the mobile ad-hoc network and assume that
the communication medium is reliable and that the nodes are 'well-behaved.'

[18]   Other distributed problems solved for mobile ad-hoc networks are mutual
exclusion in J. Walter, J. Welch, and N. H. Vaida, A Mutual Exclusion Algorithm
for Ad-hoc Mobile Networks, Technical Report TR99-011, Department of

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Computer Sciences, Texas A&M University, 1999 and reliable broadcast in E. Pagani and G. P. Rossi, Reliable Broadcast in Mobile Multi-hop Packet Networks, Mobile Computing and Networking, pg. 34-42, 1997. None of these works deals with the case of misbehaving nodes.

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[19] SUMMARY OF THE INVENTION

[20]   The present invention provides a method, an apparatus, and a computer program product for increasing the fault tolerance in a network. In a first aspect, operations of the present invention comprise: associating a plurality of nodes

10   with a sub-network, each of said plurality of nodes capable of sending and receiving data; adding a plurality of cross layer communication agent capable nodes, herein referred to as CCA-capable nodes, to said sub-network, said plurality of CCA-capable nodes capable of receiving data from and sending data to said plurality of nodes; and determining which CCA-capable node should be

15   assigned to be a gateway CCA, whereby said gateway CCA is used by each one of said plurality of nodes within said sub-network to communicate with the rest of the network.

[21]   In another aspect of the present invention, the operation of determining further

20   comprises designating one of the plurality of CCA-capable nodes as the gateway CCA; querying the gateway CCA from each node to determine whether it is active and awaiting a response, and when: the gateway CCA responds, repeating the querying operation; otherwise, broadcasting a solicit message for receipt by CCA-capable nodes and awaiting a response, and when: a CCA-capable node

25   responds, assigning a CCA-capable node as the gateway CCA; otherwise, repeating the broadcasting operation.

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[22]   In another aspect of the present invention, when a plurality of CCA-capable nodes responds, selecting, among the nodes, a single CCA-capable node for use by all of the nodes as the gateway CCA.

5   [23]   In another aspect of the present invention, the operation of selecting further comprises operations of: determining a network ID for each of the plurality of CCA-capable nodes responding; and selecting a CCA-capable node having a lowest network ID from each of the plurality of CCA-capable nodes responding as the gateway CCA.

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[24]   In another aspect of the present invention, the operation of determining which CCA-capable node should be assigned to be the gateway CCA further comprises designating one of the plurality of CCA-capable nodes to be a gateway CCA; querying the plurality of CCA-capable nodes, from at least one node of the

15   plurality of nodes, to determine whether they are active and awaiting a response, and when: the gateway CCA responds, repeating the querying operation; otherwise, changing the CCA-capable node assigned to be the gateway CCA based upon a response from the plurality of CCA-capable nodes.

20   [25]   In another aspect of the present invention, when more than one CCA-capable node responds, selecting, among the nodes, a single CCA-capable node for use by all of the nodes as the gateway CCA.

[26]   In another aspect of the present invention , the operation of determining which
25   CCA-capable node should be assigned to be the gateway CCA further comprises designating one of the plurality of CCA-capable nodes to be a gateway CCA; compiling a list of CCA-capable nodes on at least one CCA-capable node of the plurality of CCA-capable nodes; querying each CCA-capable node, from the at least one CCA-capable node, in the list to determine its state; updating the list of

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CCA-capable nodes based on the responses from the CCA-capable nodes; and

checking for a response from the gateway, and when: the gateway CCA responds

repeating the querying operation; otherwise, transmitting the list of CCA-capable

nodes to the plurality of nodes in the sub-network; and selecting and assigning a

5   new gateway CCA from the list of CCA-capable nodes.

[27]   In another aspect of the present invention, when more than one CCA-capable

node is in the list of CCA-capable nodes, selecting, among the nodes, a single

CCA-capable node for use by all of the nodes as the gateway CCA.

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[28]   In another aspect of the present invention , the operation of determining which

CCA-capable node should be assigned to be the gateway CCA further comprises

designating one of the plurality of CCA-capable nodes to be a gateway CCA;

querying each CCA-capable node, from at least one CCA-capable node in the

15   plurality of CCA-capable nodes, in the list to determine its state; updating the list

of CCA-capable nodes based on the responses from the CCA-capable nodes;

sending, from the at least one CCA-capable node, the list of CCA-capable nodes

to the plurality of nodes in the sub-network; waiting to repeat the querying

operation; and checking, by at least one of the nodes in the plurality of nodes, the

20   list of CCA-capable nodes for the gateway CCA, and when: the gateway CCA is

in the list of CCA-capable nodes waiting for the next list of CCA-capable nodes;

otherwise, selecting and assigning a new gateway CCA from the list of CCA-

capable nodes.

25 [29]   In another aspect of the present invention, when more than one CCA-capable

node is in the list of CCA-capable nodes, selecting, among the nodes, a single

CCA-capable node for use by all of the nodes as the gateway CCA.

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[30]   In another aspect of the present invention, the operation of determining which CCA-capable node should be assigned to be the gateway CCA further comprises designating one of the plurality of CCA-capable nodes to be a gateway CCA; broadcasting a message from each CCA-capable node to the plurality of nodes; and selecting a gateway CCA based upon the message from each CCA-capable node.

[31]   In another aspect of the present invention, the operation of selecting a gateway CCA further comprises the operations of determining a current hop-count for the message; and comparing the current hop-count to previous hop-counts from previous messages, and when the current hop-count is less than the previous hop-count selecting the CCA-capable node which broadcast the message as a new gateway CCA.

[32]   In another aspect of the present invention, the operation of selecting a gateway CCA further comprises the operations of determining a current time at which the message was received; retrieving a gateway time at which a message from the gateway CCA was received; and selecting and assigning a new gateway CCA based upon a result of a user-specified formula for comparing the current time and the gateway time.

[33]   In another aspect of the present invention , the operation of determining which CCA-capable node should be assigned to be the gateway CCA further comprises the operations of designating one of the plurality of CCA-capable nodes to be a gateway CCA; transmitting a vote from each CCA-capable node to all other CCA-capable nodes designating which CCA-capable node should become a subsequent gateway CCA; and tallying said votes for each CCA-capable node, and when: one CCA-capable node receives more votes than any of the other

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CCA-capable nodes, assigning the one CCA-capable node to become the new gateway CCA, otherwise repeating the transmitting operation.

[34]   In another aspect of the present invention, the operation of determining which CCA-capable node should be assigned to be the gateway CCA further comprises the operation of determining if at least 2/3 of the plurality of CCA-capable nodes are active, and wherein at least 2/3 of the CCA-capable nodes must respond before performing the operation of transmitting the vote.

[35]   In another aspect of the present invention, the operation of associating the plurality of nodes further comprises an operation of associating the plurality of nodes in an ad-hoc manner.

[36]   In another aspect of the present invention, the method, apparatus, and computer program product further comprise the operation of enabling the plurality of nodes and CCA-capable nodes to be mobile.

[37]   One skilled in the art will appreciate that the operations presented above can be interpreted as computer instructions, an apparatus configured to perform the operations, or as processing acts of a method.

[38]   BRIEF DESCRIPTION OF THE DRAWINGS

[39]   The objects, features and advantages of the present invention will be apparent from the following detailed descriptions of the preferred aspect of the invention in conjunction with reference to the following drawings where:

[40]   FIG. 1 is a prior art block diagram of a hybrid network;

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[41]   FIG. 2 is a block diagram depicting components in a sub-network in accordance
with the present invention;

[42]   FIG. 3 is an illustrative diagram of a computer program product aspect of the

5   present invention;

[43]   FIG. 4 is an illustrative diagram of a node in accordance with the present
invention;

10   [44]   FIG. 5 is an illustrative diagram of a Cross Layer Communication Agent capable
(CCA-capable) node in accordance with the present invention;

[45]   FIG. 6 is a flow diagram of the node-initiated and reactive algorithm in
accordance with the present invention;

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[46]   FIG. 7 is a flow diagram of the node-initiated and proactive algorithm in
accordance with the present invention;

[47]   FIG. 8A is a flow diagram of one prospective example of the CCA-initiated and

20   reactive algorithm in accordance with the present invention;

[48]   FIG. 8B is a flow diagram of a second prospective example of the CCA-initiated
and reactive algorithm in accordance with the present invention;

25   [49]   FIG. 9 is a flow diagram of the CCA-initiated and proactive algorithm in
accordance with the present invention; and

[50]   FIG. 10 is a flow diagram of a CCA selection algorithm for security in accordance
with the present invention.

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[51]   DETAILED DESCRIPTION

[52]   The present invention relates to techniques for security and fault tolerance in hybrid wireless networks. Specifically, the invention relates to a system and method to allow and utilize multiple Cross Layer Communication Agents in a single sub-network for increased fault tolerance. The following description, taken in conjunction with the referenced drawings, is presented to enable one of ordinary skill in the art to make and use the invention and to incorporate it in the context of particular applications. Various modifications, as well as a variety of uses in different applications, will be readily apparent to those skilled in the art, and the general principles defined herein, may be applied to a wide range of aspects. Thus, the present invention is not intended to be limited to the aspects presented, but is to be accorded the widest scope consistent with the principles and novel features disclosed herein. Furthermore, it should be noted that unless explicitly stated otherwise, the figures included herein are illustrated diagrammatically and without any specific scale, as they are provided as qualitative illustrations of the concept of the present invention.

[53]   In order to provide a working frame of reference, first a glossary of terms used in the description and claims is given as a central resource for the reader. Next, a discussion of various principal aspects of the present invention is provided. Finally, a discussion is provided to give an understanding of the specific details.

[54]   (1) Glossary

[55]   Before describing the specific details of the present invention, a centralized location is provided in which various terms used herein and in the claims are defined. The glossary provided is intended to provide the reader with a general understanding for the intended meaning of the terms, but is not intended to convey the entire scope of each term. Rather, the glossary is intended to

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supplement the rest of the specification in more accurately explaining the terms used.

[56]   CCA-capable nodes – Cross-layer communication agent capable nodes are nodes
5   capable as serving as gateways for interfacing between the various components of
          the hybrid network, or for interfacing between two sub-networks.

[57]   Hybrid network – A network comprising different components (heterogeneous)
          utilizing different transmission/reception equipment and/or protocols such as
10   satellite networks combined with fixed and mobile multi-hop terrestrial networks.

[58]   Nodes – Network components capable of transmitting and receiving data to and
          from each other within a sub-network.

15 [59] Sub-network – A sub-network comprises a collection of components that utilize
          the same (homogeneous) transmission/reception equipment to communicate with
          each other. A sub-network is a smaller portion of a larger hybrid network.

20
     [60]   (2) Principal Aspects
     [61]   The present invention has three principal aspects. The first is a node or sub-
             network of nodes. The sub-network includes a plurality of nodes and CCA-
             capable nodes. Running on the CCA-capable nodes and non-CCA-capable nodes
25   are instructions, typically in the form of software operating on a computer system
             or in the form of a "hard-coded" instruction set. The second principal aspect is a
             method, typically in the form of software, operated using a data processing system
             (computer). The third principal aspect is a computer program product. The
             computer program product generally represents computer readable code stored on

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a computer readable medium such as an optical storage device, e.g., a compact disc (CD) or digital versatile disc (DVD), or a magnetic storage device such as a floppy disk or magnetic tape. Other, non-limiting examples of computer readable media include hard disks, read only memory (ROM), and flash-type memories.

5   These aspects will be described in more detail below.

[62]   A block diagram depicting the components of a sub-network of the present invention is provided in FIG. 2, where icons are used for clarity and are not intended to limit the type of nodes or CCA-capable nodes. The sub-network 200

10   comprises a plurality of nodes 201 – 209 and a plurality of CCA-capable nodes 221-226. Each CCA-capable node 221-226 is equipped to provide a gateway for each of the plurality of nodes 201-209 to access other portions of the hybrid network, as discussed in relation to FIG. 1. One skilled in the art will appreciate that each CCA-capable node 221-226 may also be a node for communicating with

15   the other nodes 201-209 in the sub-network 200.

[63]   An illustrative diagram of a computer program product aspect of the present invention is depicted in FIG. 3. The computer program product 300 is depicted as an optical disk such as a CD or DVD. However, as mentioned previously, the

20   computer program product generally represents computer readable code stored on any desirable computer readable medium.

[64]   An illustrative diagram of a node is depicted in FIG. 4. As shown, the node 400 includes a data processing system 402 and a signal transmitter/receiver 404

25   coupled therewith. The signal transmitter/receiver 404 may be an omni-directional transmitter/receiver, or may be configured directionally if desired. While the transmitter/receiver 404 is shown in FIG. 2 to be RF, many other mediums such as millimeter wave (MMW), infra-red (IR), acoustic, etc. may be used.

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[65]   An illustrative diagram of a CCA-capable node is depicted in FIG. 5. As shown, the node 500 includes a data processing system 502 coupled with both a signal transmitter/receiver 504 and a cross-layer transmitter/receiver 506. The signal transmitter/receiver 504 maybe an omni directional transmitter/receiver, or may be configured directionally if desired. The cross-layer transmitter/receiver 506 is depicted in FIG. 2 as a satellite transmitter/receiver, but one skilled in the art will appreciate that the cross-layer transmitter/receiver 506 could be any type of transmitter/receiver required to communicatively connect the CCA-capable node 500 with the other components of the hybrid network whether it be a satellite network, a fixed network, an airborne network, or any other type of network. Further, one skilled in the art will appreciate that the signal transmitter/receiver 504 and the cross-layer transmitter/receiver 506 maybe the same physical transmitter/receiver depending upon the configuration of the sub-network and the hybrid network.

[66]   In the illustration, the hybrid network is a satellite network and an ad-hoc wireless network. One skilled in the art will appreciate that the functions of transmitting and receiving signals from the hybrid network to the CCA-capable nodes may be split between two CCA-capable nodes, wherein one CCA-capable node transmits to the hybrid network, while a second CCA-capable node receives from the hybrid network. This implementation would require messaging between the CCA-capable nodes being used as transmitter and receiver.

[67]   (3) Introduction

[68]   The present invention provides a mechanism by which many CCA-capable nodes within a sub-network can take turns being the primary gateway, providing cross-layer connectivity, and thus ensuing fault tolerance in case of gateway CCA failures. For the hybrid network architecture described thus far, it is evident that a

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single gateway CCA in the sub-network is a single point of failure. The solution proposed comprises a plurality of CCA-capable nodes that otherwise function as regular nodes in the sub-network. At pseudo-random times, the responsibility of being the gateway is rotated among the CCA-capable nodes in an authenticated

5   and distributed manner. This provides a measure of security against hostile attacks on the system that may compromise the connectivity or data integrity of the network. Thus, a few of the capabilities of a network of the present invention include:

10   [69]   • Ability to detect failures among CCA-capable nodes and to coordinate the selection and initiation of backup gateway CCAs;

        • Ability to randomly and securely rotate the responsibility of being a gateway CCA among a group of CCA-capable nodes; and

15

        • Ability to implement a secure and distributed fault tolerance system by designing the relevant network control features such as routing and medium access control messages.

20   [70]   One aspect of the present invention is to provide fault tolerance and security in the operation of CCA-capable nodes in a hybrid network, such as a satellite, mobile multi-hop network. The techniques employed also enable the network to be self-recovering and to have a graceful degradation in network performance in the face of failures; either unintentional or malicious.

25

    [71]   The system and method comprises of a group of protocols that enable Cross Layer Communication Agents (CCAs) to incorporate a measure of security and distributed fault tolerance during normal operations. The subject matter is explained through the illustration of a wireless, ad-hoc, hybrid network consisting

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of satellites and mobile nodes. For purposes of this example and clarity of explanation, it is assumed that the nodes are clustered into sub-network groups, and the objective is to enable reliable, secure communications among the various nodes. As previously discussed, CCA nodes serve to extend the range and

5   connectivity of the sub-network of mobile nodes.

[72]   (4) Assumptions

[73]   The fault tolerance algorithms disclosed herein are primarily designed to be implemented as software protocols on computing devices operating as part of a

10   hybrid network, as shown in FIGs. 1 and 2. One skilled in the art will appreciate that these algorithms may also be implemented in firmware or hardware. The algorithms rely on underlying and overlying systems and software modules for complete system operation. The following assumptions will assist the reader in understanding the context under which these algorithms are preferably used.

15

[74]   First - The fault tolerance algorithms are network programs residing at the network layer and/or transport layer of the 7 layer Open Source Initiative (OSI) model. The algorithms preferably interact with the routing protocol to direct the formation/destruction of routes within the ad-hoc sub-network.

20

[75]   Second - The network employs standard medium access control (MAC), Routing or Physical Layer protocols.

[76]   Third - The network may have application-level or packet-level encryption/data

25   authentication, but strong encryption and mutual authentication is preferable for passing the control messages among the CCA-capable nodes executing the fault-tolerance algorithms. This is to prevent Byzantine attacks from unauthorized nodes.

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[77]   Fourth - During initial deployment, all the CCA-capable nodes in an ad-hoc sub-
network are aware of each other's identity (e.g. authentication public key,
network address etc.).

5   [78]   Fifth - During normal operations, only one CCA-capable node per ad-hoc sub-
network is active, thus serving as a gateway CCA for that sub-network. A backup
gateway CCA is activated from the group of CCA-capable nodes in response to
failures or for security/alteration reasons. There is no system architectural
limitation that prevents multiple gateway CCAs from operating simultaneously.
10   One skilled in the art will appreciate that having multiple CCAs operating
simultaneously increases the overhead (e.g. in handoff, tracking, power
conservation etc. for the mobile nodes in the group).

[79]   Sixth - During initialization and boot-up, the CCA-capable node with the lowest
15   network ID assumes the task of being the gateway CCA and floods the network
with its identification information. Standard underlying protocols are used to
ensure authentication (e.g., by digital signatures, etc.) for the other nodes in the
network.

20   [80]   Seventh - Since CCA-capable nodes are expected to be GPS-enabled, a common
synchronization clock is assumed to be available to all the CCA-capable nodes for
reconciling time-out clocks and timers for the distributed algorithms.

[81]   The system and method disclosed herein can be applied to any hybrid network,
25   including a satellite/mobile ad-hoc hybrid network that is deployed in a terrain
with blockages and communication impairments (e.g., applications involving
physically separated groups communicating with mobile CCA-capable nodes in
harsh fading/jammed communication environments with blockages and high
failure hazards). Other applications are also possible in industrial settings where

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5 mobile sensors or systems are needed to monitor or control a distributed process (e.g., physical packages being automatically routed and delivered, raw materials being handled remotely in the process line-up of a manufacturing plant, etc.) or for security applications, and situations where the information from the mobile robotic sensors is aggregated at a single concentrator node or gateway.

[82] (5) Discussion

[83] As previously described, the techniques disclosed herein enable recovery from the failure of a sub-network gateway CCA when connected with a larger hybrid network. Further, the techniques described herein provide for a more secure network. First, techniques for enabling recovery from failure will be discussed, followed by techniques that can be used to enhance the security in addition to recovering from failures.

[84] I. Recovery from Failures

[85] Failures of a gateway CCA include both (i) fail-stop failures, and (ii) intermittent failures. In fail-stop failures, the number of CCA-capable nodes that are available in a sub-network is permanently reduced (e.g., through destruction or power/operational outage). In contrast, for intermittent failures, CCA-capable nodes are temporarily disabled as these nodes experience intermittent connectivity (e.g., terrain) blockages. However, in the case of intermittent failures, the total number of simple nodes (non-CCA-capable nodes) is increased since the CCA-capable nodes may also operate as simple nodes.

[86] There are several solutions for these failures. The solutions have been broadly divided into two categories for clarity: (1) node-initiated and (2) CCA-initiated. The solutions for each category can be further sub-divided into two groups: (a) reactive and (b) proactive. Thus, there are four possible combinations of solutions, and the algorithms corresponding to these solutions are outlined in

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general flowchart form in FIGs. 6 - 9. The algorithms themselves are described below. For estimating the numerical order for the control messages generated for each strategy, a network consisting of m nodes and n CCA-capable nodes per ad-hoc sub-network is assumed. Herein the term "nodes" refers both to nodes that

5   are not CCA-capable and to CCA-capable nodes that are operating as non-CCA-capable nodes.

[87]   (a) Node-Initiated and Reactive

[88]   FIG. 6 is a flow diagram of the node-initiated and reactive algorithm. As

10   previously discussed in section 4 entitled Assumptions, the CCA-capable node having the lowest network ID is initially assigned as the gateway CCA. In reference to FIG. 2 and FIG. 6, an action of designating a gateway CCA 602 is preformed in which a CCA-capable node 221 is assigned as the gateway CCA. In the node-initiated and reactive case, each node 201-209, 222-226 starts a search

15   for a new gateway CCA when it finds its current gateway CCA 221 to be inactive. Each node 201-209, 222-226 periodically queries the 'liveness' status of its gateway CCA 221 (which indicates if the CCA is functional), by pinging the gateway CCA 221 after the action of waiting a time T_1 604. Time T_1 is chosen based upon the needs of a particular application. For example, if the sub-network

20   200 is time critical, T_1 may be a small number on the order of milliseconds to ensure that any failure in the gateway CCA 221 will be quickly determined. However, if the sub-network is less important, T_1 may be chosen to be a longer duration. Another consideration for determining T_1 is the speed at which the nodes 201-209, 222-226 are traveling.

25

[89]   Each node 201-209, 222-226 performs an action of querying the gateway CCA 606, in which each node 201-209, 222-226 sends a GATEWAY_STATUS query message 606 to its gateway CCA 221, and sets its timer T_1 equal to zero. The node 201-209, 222-226 then performs an action of waiting for a KEEP_ALIVE

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message 608, wherein the node 201-209, 222-226 expects the gateway CCA 221 to respond with a KEEP_ALIVE message within a desired retransmission time-out (RTT) amount of time 608. If no such response is received, the node 201-209, 222-226 performs an action of broadcasting a CCA_SOLICIT message 610 wherein the node 201-209, 222-226 transmits the CCA_SOLICIT. The node 201-209, 222-226 then performs the action of waiting for an ADVERTISEMENT message 612, wherein the node 201-209, 222-226 waits for an ADVERTISEMENT message from any active CCA-capable node 222-226 for T_2 units of time. As previously discussed with relation to T_1, the time period T_2 will also be application-dependent. Time period T_2 can also be dependent upon the environment in which the sub-network 200 is placed.

[90]   The node 201-209, 222-226 keeps retrying for every T_2 units of time until a CCA-capable node 222-226 sends an ADVERTISEMENT message. For purposes of discussion, assume that CCA-capable nodes 222-226 responded with an ADVERTISEMENT message. The node 201-209, 222-226 performs the action of selecting and assigning a gateway CCA 614, wherein one of the CCA-capable nodes 222-226 that responded is selected and assigned to be the new gateway CCA. One skilled in the art will appreciate that there are a variety of different methods that may be used to select which CCA-capable node 222-226 that responded with an ADVERTISEMENT message will be assigned to be the new gateway CCA. For example, in one aspect, a node 201-209, 222-226 may choose as its new gateway CCA the CCA-capable node that has the lowest network ID 222 from the CCA-capable nodes 222-226 that respond with an ADVERTISEMENT message. An example of network IDs may be the IP-address of the CCA-capable node 221-226 or even assigned IDs such as the reference numerals in the FIGs. This whole procedure is repeated every T_1 units of time. The broadcast messages need to reach beyond a single hop in the ad-hoc

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network. Consequently, all nodes rebroadcast a broadcast message upon receiving one for the first time.

[91]   The resulting number of GATEWAY_STATUS and KEEP_ALIVE messages that flow through the network is $2m*(1/T_1)$ unicast messages per unit time. However, when a CCA is determined to be inactive, there will be a flood of m CCA_SOLICIT broadcast messages in the worst case and 1/m broadcast messages for the average case. The replies to CCA_SOLICIT messages are unicast messages and can be up to (n-1)*m messages in the worst case and (n-1) for the average case.

[92]   (b) Node-Initiated and Reactive

[93]   In the node-initiated and reactive case, each node keeps track of all active CCA-capable nodes by periodically pinging all the CCA-capable nodes. When the gateway CCA that the node is affiliated with does not respond to ping messages, the node switches to one of the CCA-capable nodes that recently responded to its ping message. FIG. 7 is a flow diagram of the node-initiated and proactive algorithm. In this algorithm, the nodes have to keep track of all the CCA-capable nodes in the network. This is useful for fast recovery if the gateway CCA becomes inactive, but at the cost of an increase in the overhead.

[94]   As shown in FIG. 7, each node 201-209, 222-226 performs a waiting action 702, wherein each node 201-209, 222-226 waits a time T_1. As explained in the previous section, T_1 will vary depending upon the specific implementation of the sub-network 200. Each node 201-209, 222-226 then performs an operation of querying the CCA-capable nodes 704, wherein each node 201-209, 222-226 sends a STATUS_QUERY message to all of the known CCA-capable nodes 221-226 and setting a timer. Each CCA-capable node 221-226 that is active, i.e. has not been destroyed, is not blocked by terrain, or has power and is capable of

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responding, performs an operation of responding with its status 704 by sending a KEEP_ALIVE message back to the node 201-209, 222-226. Each node 201-209, 222-226 performs an operation of checking for its gateway CCA 706 by collecting the KEEP_ALIVE messages and determining if its gateway CCA 221

5   responded with a KEEP_ALIVE message within a desired retransmission time-out (RTT) amount of time. If the gateway CCA 221 responded, then the node 201-209, 222-226 performs the waiting action 703 and the process repeats. If the gateway CCA 221 does not respond, then the node will perform an operation of finding a new gateway 708, in which the node 201-209, 222-226 determines if

10   any of the other CCA-capable nodes 222-226 have responded within the desired RTT amount of time. If another CCA-capable node 222-226 has responded within RTT period, the node 201-209, 222-226 will perform an operation of selecting and assigning a new gateway CCA 710. One skilled in the art will appreciate that there are a variety of different methods that may be used to select

15   which CCA-capable node 222-226, responding with a KEEP_ALIVE message, will be designated as the new gateway CCA. For example, in one prospective example, a node may choose as its new gateway CCA 222, the CCA-capable node that has the lowest network ID from the CCA-capable nodes that responded with a KEEP_ALIVE message. Thus, if CCA-capable nodes 222, 224 and 226

20   respond, node 201 may choose CCA-capable node 222 as its new gateway CCA.

[95]   If no CCA-capable nodes 221-226 respond to the node's 201-209, 222-226 KEEP_ALIVE message before the RTT period expires, the node 201-209, 222-226 will repeat the operation of querying the CCA-capable nodes 704.

25

[96]   The number of messages in normal case is $m*n*(1/T_1)$ unicast messages per unit time. When a failure is detected, the switch-over time to a new gateway CCA is close to zero in most cases, and is the same as for the node-initiated, reactive case when no other CCA-capable node responds to CCA_STATUS query message.

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[97]   (c) CCA-Capable Node-Initiated and Reactive

[98]   For the CCA-capable node-initiated reactive case, each CCA-capable node keeps
       track of the active CCA-capable nodes. FIG. 8A is a flow diagram of one
5   prospective example of the CCA-initiated and reactive algorithm. At the
       beginning of the algorithm 802, each CCA-capable node 221-226 knows the list
       of CCA-capable nodes 221-226 present in the sub-network 200. In addition, each
       node 201-201, 222-226 is initially assigned to a gateway CCA 221. Each CCA-
       capable node 221-226 also performs an operation of setting a retry-counter 804,
10   wherein the retry-counter is initially set to zero. Each CCA-capable node 221-
       226 performs an action of waiting 806, wherein each CCA-capable node 221-226
       waits for a time period T_1. As previously discussed the time period T_1 is
       application specific.

15 [99] After waiting, each CCA-capable node 221-226 performs an operation of
       querying each CCA-capable node 808, wherein each CCA-capable node 221-226
       sends the KEEP_ALIVE message to all other CCA-capable nodes 221-226 and
       sets a timer t=0. Each CCA-capable node 221-226 responds to another CCA-
       capable node's KEEP_ALIVE message with an acknowledgment message
20   (KEEP_ALIVE_ACK). Each CCA-capable node 221-226 performs an operation
       of updating 810, wherein each CCA-capable node 221-226 updates its list of
       CCA-capable nodes based on the KEEP_ALIVE_ACK messages from the other
       CCA-capable nodes.

25 [100] Each CCA-capable node 221-226 then performs an operation of checking for
       gateway CCA response 812, wherein each CCA-capable node 221-226 checks to
       see if the gateway CCA 221 has responded with a KEEP_ALIVE_ACK message.
       If the gateway CCA 221 has responded, the CCA-capable node 221-226 resets the
       retry-counter and the algorithm is repeated. If the gateway CCA 221 does not

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respond, the CCA-capable node 221-226 performs an operation of incrementing the retry-counter 814, wherein the CCA-capable node 221-226 preferably updates the retry-counter by one. Then, the CCA-capable node 221-226 performs an operation of comparing 816, wherein the CCA-capable node 221-226 compares

5   the value of the retry-counter to a predetermined max number of retries. One skilled in the art will appreciate that under certain conditions, the max number of retries may be set to 1 or a retry-counter may not be implemented, if the application requires quick determination that a gateway CCA is not active.

10 [101]   If the max number of retries has not been exceeded, the CCA-capable node will re-perform the operation of sending a KEEP_ALIVE message 808. A particular CCA-capable node 221-226 is generally labeled as inactive if this CCA-capable node does not respond to a predetermined number of multiple retries of the KEEP_ALIVE message transmissions. One skilled in the art will appreciate that

15   a retry-counter may be used to collect the number of times that a CCA-capable node (which is not a gateway CCA) has not responded to a KEEP_ALIVE message.

[102]   If the gateway CCA 221 does not respond after the max number of retries, i.e., it

20   is found to be inactive, each CCA-capable node 222-226 performs an operation of sending the list of active CCA-capable nodes 818, wherein each CCA-capable node 221-226 transmits to all of the other nodes 201-209, 221-226 the list of CCA-capable nodes have responded to the KEEP_ALIVE message and are thus active. The nodes 201-209, 222-226 previously using the inactive CCA-capable

25   node 221 as their gateway CCA next perform an operation of selecting and assigning a new gateway CCA 820, wherein each node 201-209, 222-226 selects and assigns as its new gateway CCA a CCA-capable node that is active and within its communication range. One skilled in the art will appreciate that there are a variety of different methods that may be used to determine which CCA-

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capable node in the list of active CCA-capable nodes will be assigned to be the new gateway CCA. For example, in one prospective example, a node may choose as its new gateway CCA, the CCA-capable node that has the lowest network ID from the list of CCA-capable nodes.

5

[103]   FIG. 8B is a flow diagram of a second prospective example of the CCA-initiated and reactive algorithm. At the beginning of the algorithm 852, each CCA-capable node 221-226 knows the list of CCA-capable nodes 221-226 present in the sub-network 200. In addition, each node 201-201, 222-226 is initially assigned to a

10   gateway CCA 221. Each CCA-capable node 221-226 performs an action of waiting 856, wherein each CCA-capable node 221-226 waits for a time period T_1. As previously with respect to FIG. 6 above, the time period T_1 is application specific.

15 [104]   After waiting, each CCA-capable node 221-226 performs an operation of sending a KEEP_ALIVE message 858, wherein each CCA-capable node 221-226 sends the KEEP_ALIVE message to all other CCA-capable nodes 221-226 and sets a timer t=0. Each CCA-capable node 221-226 responds to another CCA-capable node's KEEP_ALIVE message with an acknowledgment message

20   (KEEP_ALIVE_ACK). Each CCA-capable node 221-226 performs an operation of updating 860, wherein each CCA-capable node 221-226 updates its list of active CCA-capable nodes based on the KEEP_ALIVE_ACK messages it receives.

25 [105]   Each CCA-capable node 221-226 next performs an operation of sending 868, wherein each CCA-capable node 221-226 sends the list of CCA-capable nodes 222-226 that are active to all the nodes 201-209, 222-226. The nodes 201-209, 222-226 receive the list of active CCA-capable nodes 222-226 and perform an operation of checking 872, wherein each node 201-209, 222-226 checks to see if

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its current gateway CCA 221 is in the list of active CCA-capable nodes 222-226.
If the gateway CCA 221 is in the list of active CCA-capable nodes, then the node
201-209, 222-226 enters a wait state 826 until the next list of CCA-capable nodes
is received. If the gateway CCA 221 is not in the list of active CCA-capable

5   nodes 222-226 then the node 201-209, 222-226 performs operations of selecting
and assigning 824, wherein the node 201-209, 222-226 selects and assigns a new
gateway CCA in its communication range from the list of active CCA-capable
nodes 222-226. One skilled in the art will appreciate that there are a variety of
different methods that may be used to determine which CCA-capable node in the

10   list of active CCA-capable nodes will be assigned to be the new gateway CCA.
For example, in one prospective example, a node may choose as its new gateway
CCA, the CCA-capable node that has the lowest network ID from the list of
CCA-capable nodes.

15 [106] In the CCA-capable node-initiated reactive case, there is a flow of $n*(n-1)*1/T_1$
unicast messages per unit time and n-1 broadcast messages upon detection of a
faulty CCA-capable node. The detection time is $T_1/2$ seconds, on the average.

    [107]   (d) CCA-capable node-Initiated and Proactive

20 [108] FIG. 9 is a flow diagram of the CCA-initiated and proactive algorithm. Each
CCA-capable node 221-226 performs an action of waiting 902, wherein each
CCA-capable node 221-226 waits for a time period T_1. As previously discussed
in relation to FIG. 6 above, the time period T_1 is application specific.

25 [109] After waiting time period T_1, each CCA-capable nodes 221-226 performs an
operation of broadcasting an ADVERTISEMENT message 904, wherein each
CCA-capable nodes 221-226 broadcasts an ADVERTISEMENT message to all
nodes 201-209, 221-226. Each node 201-209, 221-226 that receives such a
message from a CCA-capable node 221-226 performs the operation of deciding to

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switch 906, wherein each node 201-209, 221-226 decides whether to switch its gateway CCA to a new CCA-capable node 221-226 based upon user-specified metrics. Two possible user-specified metrics are: (i) hop count and (ii) a user-specified formula that compares last time, T_{last} at which an ADVERTISEMENT message was received from the current gateway CCA. If the hop count to the new CCA-capable node 221-226 is less than the current gateway CCA's hop count, or if the user-specified formula $T_{last} < (current\_time - 2*(T_1))$ is true, then the node sets the 'better' CCA-capable node as its new gateway CCA. One skilled in the art will appreciate that in this algorithm, several different CCA-capable nodes may be used by the various nodes as gateway CCAs.

[110]   This CCA-capable node-initiated proactive solution requires $n*1/T_1$ number of broadcast messages per unit time, where $1/T_1$ is the frequency of ADVERTISEMENT message broadcasts. The switchover time upon detection of a faulty CCA is negligible, but the detection time itself is $T_1*(3/2)$ units, on the average.

[111]   (e) Failure Recovery Considerations

[112]   One skilled in the art will appreciate that each of the algorithms discussed above has advantages and disadvantages regarding its overhead, response and implementation. As with any network, the best solution depends on the needs of the system. For example, if using the number of messages exchanged, detection time and switchover times as parameters, the CCA-capable node-initiated solutions are desirable since they can make use of the connectivity though the hybrid network, and also present low overhead on the communication infrastructure in the sub-network. Specifically, when looking to the number of messages, the CCA-capable node-initiated and reactive solution is optimal because all the messaging is only between CCA-capable nodes.

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[113]   II. Security

[114]   As previously discussed, in some applications, the gateway CCA may be
confiscated and manipulated by a hacker or someone desiring to disrupt the
network communications. The confiscated/manipulated CCA is henceforth
referred to as a "malicious CCA." One problem that arises as a result of the
manipulation is that if this CCA-capable node manages to become the gateway
CCA, either during a regular gateway CCA rotation step or by subterfuge, then all
communication in the system is rendered insecure, or worse. The ideal fault-
tolerance goal for this scenario is to prevent the malicious node from becoming
the gateway CCA, or from interfering in the gateway CCA selection or data
routing tasks.

[115]   A gateway CCA attracts a lot of communication from nearby nodes as part of its
regular function of routing packets to and from the sub-network. However, an
analysis of the traffic pattern might reveal the position information of the gateway
CCA, thus making it susceptible to attacks or confiscation. To avoid these
problems (as well as for power conservation reasons), it is clear that no CCA-
capable node 221-226 should be the gateway CCA for long periods. Instead, the
task of being the gateway CCA in a sub-network should be rotated among the
CCA-capable nodes 221-226 in the sub-network 200. In addition, no node 201-
209, 221-226 should use the same gateway CCA for communication for long
periods. This is to avoid a malicious node from claiming to be the gateway CCA
and controlling the packets transmitted and received from that node. This also
avoids the collection of contiguous encrypted packets of data by the malicious
CCA, where the contiguity may become helpful in decrypting the data or
revealing of the key used to encrypt the data.

[116]   FIG. 10 is a flow diagram of a CCA selection algorithm for security in which the
algorithm that assigns the role of the gateway CCA among the CCA-capable

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nodes 221-226 in a pseudo-random fashion. This algorithm follows at least these three criteria:

    i. No gateway CCA should be allowed to be active for a long period of time;

5   ii. No node should use a single gateway CCA for a long period of time; and

    iii. The order in which CCA-capable nodes become gateway CCAs should not be pre-decided or predictable.

10 [117]   If the selection sequence is pre-decided, then the confiscation of a CCA-capable node will allow the malicious node to know in advance exactly the times when each CCA becomes the gateway CCA. It will also know which gateway CCA is being used by each node. To avoid this vulnerability, the gateway CCA selection algorithm follows the following fourth criterion: i.e. a gateway CCA should be 15 selected just prior to that time period where it will be the gateway CCA, by at least a majority of CCA-capable nodes participating in the selection procedure. This is a distributed majority selection problem, which is a modified form of the 'Byzantine Generals Problem' that has been extensively studied in L. Lamport, R. Shostak and M. Pease, The Byzantine Generals Problem, ACM Transactions on 20 Programming, Language and Systems, 4(3), July 1982, pp. 382-401. For the case of CCAs in mobile ad-hoc networks, the general algorithm has been modified to satisfy all four criterion above.

[118]   (a) The Gateway CCA Selection Algorithm.

25 [119]   The general flowchart of the CCA selection algorithm is shown as FIG. 10. The precondition for this algorithm is that every CCA-capable node 221-226 knows the list of all other CCA-capable nodes 221-226 in the ad-hoc sub-network 200. The same KEEP_ALIVE-based mechanism as described in previous sections is used. The properties of the CCA-capable nodes assumed in this system are: (i)

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the CCA-capable nodes are synchronized (almost synchronized because of accessibility to GPS for all CCA-capable nodes), (ii) the messages may be lost, and (iii) not all CCA-capable nodes are reliable.

5 [120]   The gateway CCA selection algorithm has two phases. During the initialization phase, each CCA-capable node 221-226 looks up its list of all other known CCA-capable nodes in its sub-network 200 and performs a status query operation 1002, wherein each CCA-capable node 221-226 queries all other CCA-capable nodes 221-226 to determine their states. Next, each CCA-capable node 221-226 forms a

10   list of 'voting CCAs,' wherein the list comprises CCA-capable nodes which responded to the status query message. When there is a malicious CCA-capable node among this group of voting nodes, then at least four CCA-capable nodes are required to be active, otherwise the impossibility situation of the Byzantine Generals Problem occurs. If there are less than four CCA-capable nodes, the

15   default operation mode would be for each CCA-capable node to assume the role of being the gateway CCA for all the nodes within one hop distance of itself (each node that is within one hop distance of more than one CCA-capable node decides locally which CCA-capable node to use as its gateway CCA). Thus, if less than four CCA-capable nodes respond to the status query message, then the sub-

20   network is partitioned to accommodate multiple gateway CCAs, each gateway CCA servicing the nodes closest to it in order to minimize the data manipulation activities of the malicious node. The CCA-capable nodes 221-226 also perform an action of informing 1004, wherein the CCA-capable nodes 221-226 inform a command and control center of the impossibility situation. Then, if necessary,

25   depending upon the application scenario, the nodes may choose to stop transmitting all sensitive inter-sub-network data altogether.

[121]   If the impossibility situation mentioned above does not occur, i.e. more than four CCA-capable nodes are active, then each CCA-capable node 221-226 performs an

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operation of waiting 1006, wherein each CCA-capable node 221-226 waits a random time between 0 to T_{1max}. As discussed above, T_{1max} is chosen based upon the specific application in which the sub-network 200 is being used. The CCA-capable node 221-226 then performs an operation of generating its vote 1008,

5   wherein each CCA-capable node 221-226 votes for the new gateway CCA from the list of active CCA-capable nodes 221-226, excluding the current gateway CCA 221 as a possible candidate.

[122]   The CCA-capable node 221-226 then performs an operation of encrypting its vote

10   1008, wherein each CCA-capable node 221-226 encrypts its vote using underlying encryption technology, and transmits its vote to all the other CCA-capable nodes 221-226 in the active list. Next, each CCA-capable node 221-226 performs an action of tallying, wherein each CCA-capable node 221-226 collects and tallies the votes sent by the other CCA-capable nodes within time period

15   T_{2max}. One skilled in the art will appreciate that T_{2max} is an application-specific time parameter.

[123]   Since the communication path between CCA-capable nodes 221-226 can have intermittent failures, acknowledgement-based mechanism is preferably used (e.g.

20   IEEE 802.11) to increase the reliability of message exchange in each round.

[124]   Each CCA-capable node 221-226, then performs an operation of determining received number of votes 1012, wherein each CCA-capable node 221-226 determines if at least 2/3 of the CCA-capable nodes 221-226 responded with a

25   vote. If less than 2/3 responded, the impossibility of the Byzantine Generals problem occurs, and again the sub-network 200 is partitioned, and the CCA-capable nodes perform the action of informing 1004, wherein the command and control center is informed of the impossible situation. If at least 2/3 of the CCA-capable nodes 221-226 respond, then the CCA-capable nodes 221-226 perform an

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action of determining if there is a CCA that has received the most votes 1014,

wherein each CCA-capable node 221-226 determines if there is a CCA-capable

node which received more votes than any other CCA-capable node before time

T_{2max}, whereby the CCA-capable node receiving the most votes is the clear

5   winner. If a clear winner emerges, the CCA-capable nodes 221-226 perform the

operation of selecting and switching to this new gateway CCA 1016, wherein

each CCA-capable node 221-226 selects and switches its assigned gateway CCA

to the CCA-capable node 221-226 which received the most votes. All the nodes

201-209 are then informed of this decision by all the CCA-capable nodes 221-

10   226.

[125]   If either a timeout occurs or no clear winner emerges, then the algorithm is

repeated (up to a software settable number of times, depending upon the

application requirements).

15

[126]   The gateway CCA selection algorithm is periodically executed with large enough

timeout periods T_{1max} and T_{2max} to prevent to frequent gateway CCA changes.

Since all CCA-capable nodes are almost synchronized, each CCA-capable node

knows when the gateway CCA selection algorithm needs to be (re)started. It is

20   interesting to note that this algorithm may also be used if the current gateway

CCA is destroyed or its link with the rest of the hybrid network is blocked. Thus,

this gateway CCA selection algorithm can be used as another variation (albeit

inefficiently) of the CCA fault recovery system described earlier in the Recovery

from Failure section.

25